Towards Establishing and Maintaining Autonomous Quadrotor Formations

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Abstract: Autonomous aerial formations of multiple quadrotors can be used for payload manipulation and surveillance, and often require an external system for computation or control, in order to be decentralized. By having centrally controlled quadrotors, swarm applications can be realized without the limitations of an external system. In this paper, an algorithm is proposed to establish a swarm formation of centrally controlled quadrotors. First, a method of localization and motion planning is discussed for a single quadrotor. Next, the behavior of quadrotor swarm formations with centralized control is described. Lastly, the future direction of this research is explained.

1 INTRODUCTION

A quadrotor is an unmanned aerial vehicle (UAV) that is composed of four rotating propellers. These rotating propellers create lift and allow a quadrotor to take off and land vertically. By varying the speed each propeller rotates, quadrotors can fly agilely (Gupte et al., 2012).

Quadrotor applications broadly fall under two categories: manipulating a payload and surveillance. For payload manipulation, quadrotors are proposed for doing tasks such as delivering items; for example, the company Matternet is building the infrastructure to use quadrotors to deliver emergency products to often inaccessible, rural communities in Africa (George, 2013). Quadrotors have found surveillance application, including: riotous political movements, noninvasive inspection of buildings and public structures (Eschmann, 2012), and unsafe natural events such as mudslides and volcanoes (Waite, 2014).

While a solo quadrotor may be practical for certain tasks, multiple quadrotors cooperating towards a goal, called swarms, can be especially useful. Potential applications include: surveillance of privately property and war zones (Jaimes et al., 2008) (Culver, 2014), creating a deployable wireless communication network (Reynaud and Rasheed, 2012) (Alvissalim et al., 2012), and in disaster relief (Gupte et al., 2012).

Figure 1: Our quadrotor platform in flight.

Current swarm research operates by using an external system which decentralizes control from the quadrotor. As seen at the University of Pennsylvania and at ETH Zürich, quadrotors carry reflective beacons that are identified by multiple stationary cameras that view the testing environment. The video streamed from the cameras is interpreted by a computer to determine each quadrotor's location and state. This information is analyzed and a command is sent wirelessly to the quadrotors to actuate (Kushleyev et al., 2013) (Lupashin et al., 2010). This approach allows for sophisticated control of the quadrotors: The GRASP laboratories in the University of Pennsylvania has quadrotors performing agile swarm maneuvers (Kushleyev et al., 2013) and flying in formation at aggressive speeds (Jaimes et al., 2008). And at ETH Zürich, quadrotors have preformed controlled flips (Lupashin et al., 2010). However, decentralizing control limits quadrotor swarms to operation where they are visible to the external system.

The goal of this research is to create an autonomous quadrotor swarm with central control. Therefore, decision making and processing will be done by the quadrotor swarm. This research is towards using quadrotor swarms for surveillance, wireless communication networks, and disaster relief.

The remainder of the paper is organized as follows: Section 2 discusses the quadrotor platform devised. Section 3 describes the algorithm for a quadrotor with centralized control to localize itself with respect to a reference beacon, and system testing. Section 4 explains the algorithm designed to leverage the vision system algorithm to create an autonomous quadrotor swarm. In section 5, the initial progress in autonomous flight. Section 6 concludes the paper. Finally, section 7 discusses future work for this research.

2 QUADROTOR PLATFORM

The quadrotor system in Figure 2 is composed of a vision system and flight system. The former uses optical data to find the quadrotor's current location and compares it against a desired position to generate a movement command. The flight system is responsible for actuating the movement command and maintaining stable flight. The full system thus allows for a quadrotor to move to and maintain a desired position with respect to reference beacon.

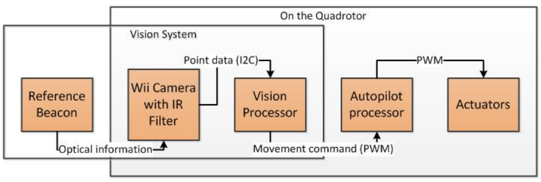

Figure 2: Quadrotor platform system flow chart.

For imaging, a Nintendo Wii controller camera was extracted, as seen in Figure 3. The Nintendo Wii controller camera, hence referred to as the Wii camera, tracks the four highest intensity light sources and outputs their Cartesian coordinate (X-Y) location. To reduce ambient light noise, the Wii camera is paired with an infrared (IR) pass filter.

The reference beacon, seen in Figure 4, is composed of four IR light emitting diodes (LEDs) denoted by $B_i(i = 1,..4)$. To reduce environmental noise,the Wii camera's capabilities are saturated by th beacon's four light sources. Localization is accomplished with information obtained from the three horizontal LEDs $B_i(i = 1,..3)$. Because B4 is not used for localization, B4 will be omitted from subsequent Figures.

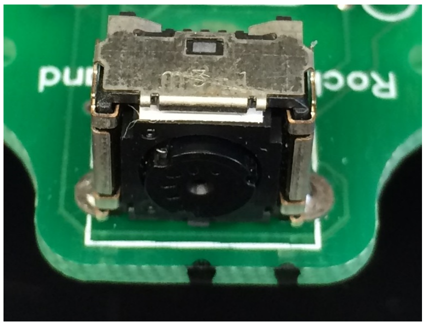

Figure 3: Nintendo Wiimote camera mounted to quadrotor frame.

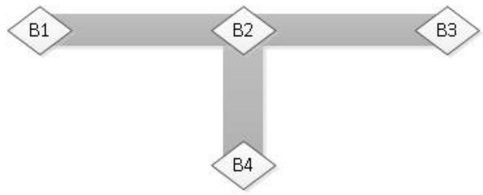

Figure 4: Reference beacon for quadrotor localization.

The Wii camera with an IR filter and beacon are ideal for our application because they allow conceptual proof of the localization algorithm without increasing the projects complexity with sophisticated image processing. It is also a benefit that the camera system is small, which reduces its footprint and its weight on the quadrotor.

3 VISION ALGORITHM

The vision processor communicates with the Wii camera to receive point data for each of the tracked IR light sources. When looking at the beacon, the quadrotor localizes itself with respect to the beacon, and moves towards the desired position. The movement action is performed so that the quadrotor can maintain sight of the beacon. When in the desired position the quadrotor hovers. Should the quadrotor be unable to find the beacon, it continues to scan in place for the reference beacon until giving up and landing.

Since movement and stability are handled by the autopilot system, if the quadrotor receives no command to move, it will maintain its altitude and location. This has allowed us to design the quadrotor to operate in a move-and-sense pattern. After each executing a movement command, the quadrotor will counter its lateral velocity. This behavior will happen several times per second, making for the appearance of smooth flight as the quadrotor seeks to maintain a location with respect to the beacon system.

3.1 Optical Metrology

For the quadrotor to determine if it is non orthogonal to the beacon, such as in Figure 5, the vision system compares the apparent difference between the beacon light source pairs: $d_{obser.B1,B2}$ and $d_{obser.B2,B3}$. If the quadrotor is non orthogonal to the beacon, $d_{obser.B1,B2} \neq d_{obser.B2,B3}$.

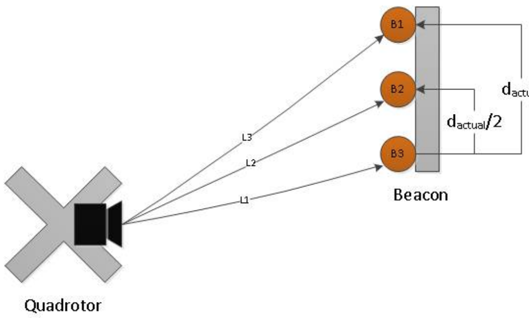

Figure 5: Topography of quadrotor non orthogonal to reference beacon.

The quadrotor determines that it is orthogonal to the beacon, such as in Figure 6, when $d_{obser.B1,B2} = d_{obser.B2,B3}$. To generalize the beacon, $d_{obser.B1.B2}$ is related to d_{obser} by equation 1. At this point, the length of the quadrotor from the beacon, defined as $L2$, can be related to d_{obser}.

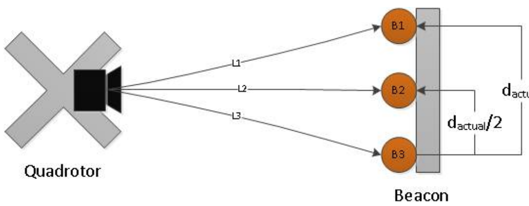

Figure 6: Topography of quadrotor orthogonal to reference beacon.

The quadrotor distance from the beacon was characterized by comparing $L2$ to d_{obser}, as shown in Figure 7. In order to make this relationship useful, the nonlinear relationship was broken up into straight line approximations. This approach seeks to provide a computationally inexpensive method to determine the quadrotors distance, $L2$, from from the beacon once orthogonal.

$$d_{obser} = (2 * d_{obser.B1,B2}) \quad (1)$$

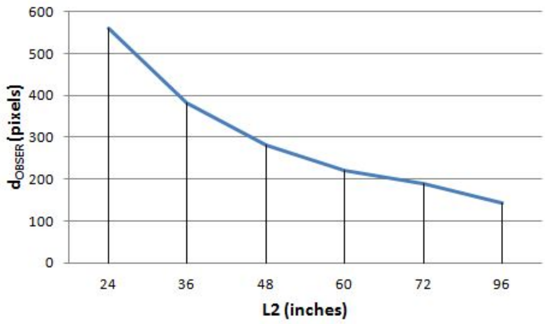

Figure 7: L2 vs d_{obser} when characterizing Wii camera.

The straight line approximation was accomplished by relating $L2$ and d_{obser} to slope intercept form, as in equation 2. In this equation, here m is the slope, and b is value of d_{obser} when the line intersects the d_{obser} axis at $L2 = 0$.

$$Y = m * X + b \;\Rightarrow\; d_{obser}(L2) = m * L2 + b \quad (2)$$

The slope, m, is determined through equation 3. In which the change in d_{obser} is compared to the change in $L2$, which are denoted by denoted by $\triangle\, d_{obser}$ and $\triangle\, L2$, respectively.

$$m = \frac{\triangle\, d_{obser}(L2)}{\triangle\, L2} \quad (3)$$

In order to solve for b, the intercept on the d_{obser}, 2 is manipulated into equation 4. b was solved through taking corresponding measured values of d_{obser} and $L2$ from Figure 7.

$$b = d_{obser} - m * L2 \quad (4)$$

Finally, the equation 2 was rearranged to create equation 5. Once m and b are solved for, this equation solves for the distance the quadrotor is from the beacon, $L2$.

$$L2 = \frac{b - d_{obser}}{m} \quad (5)$$

For our experiment, we desired a range of twenty to ninety-six inches, and the beacon was twelve inches from B1 to B3. We used equations 1-5 to develop three straight line approximations to fit the data of Figure 7. With these approximations, the calculated $L2$ was within five percent of the actual distance for the desired range.

3.2 Beacon Testing

To better understand the limitations of the vision system, it was tested against various IR LED configurations. During this experiment, we were interested to see if the camera sent data in each configuration and if that data was accurate. For consistency, the Wii camera system was mounted at a known distance and facing the reference beacon. Distance was determined when the beacon configuration passed basic checks The results of camera limits are shown in Table 1.

Table 1: System response to various beacon light source configurations. Note the following: Under the *LED Configuration* column, *o* denotes an LED emitting towards the Wii camera. In the *Data Sent* column, *In.* signifies data has been received inconsistently. All rotations and inversions of beacon configurations were tested but one case is shown to save space.

LED Configuration	Data Sent (Yes/No/In.)	Data Accurate (Yes/No)
o	No	
o o	No	
o o	No	
o o o	No	
o o o	No	
o o o o	Yes	Yes
o o o o	Yes	No
o o o o	Yes	No
o o o o o	In.	No
o o o o o	In.	No

As expected, the vision system did not send data until there were four light sources. When there are four LEDs on the horizontal line or five light sources, the system was unable to determine which light sources to use, and the data was incorrect. From these results, we learned that increased software filtering can reduce environmental noise.

The vision system's was tested under varying light conditions. It was assumed that by using the IR pass filter with the Wii camera that indoor lighting would have no noticeable impact. To validate this, the extremes of indoor lighting were tested: no light, full lighting. For both lighting conditions, the full range of the vision system was tested.

It can be observed from the results of Table 2 that for both lights on and off the Wii camera performed in the range it was designed for. Therefore, environmental lighting conditions have no effect on the vision system's ability to gain optical information from the reference beacon.

Table 2: Effect of ambient light on vision system range.

Lights	Min (in)	Maximum (in)	Range
On	20	96	100%
Off	20	96	100%

4 SWARM ALGORITHM

The purpose of the swarm algorithm is to accept the movement commands from the vision algorithm and communicate this information to respective quadrotors in the network. The communication of the movement commands will be established through a wireless medium with a wireless transceiver.

4.1 Network Topology

In the swarm network topology,the coordinator is responsible for assigning movement commands of all quadrotors in the immediate area. The coordinator will have only Wii camera systems on its platform. The followers in the swarm network only contain IR beacons on their platform, and perform commands received from the coordinator.

The swarm topology in Figure 8 shows the topology of a cluster with three followers, a coordinator, and a fixed beacon. All following quadrotors immediately adjacent to a coordinator are considered to be part of that coordinator's cluster. Within its cluster, a coordinator obtains position information from all the local followers using the process explained in the Vision Algorithm. This information is used to issue a movement command through wireless transmission in order to maintain swarm formations.

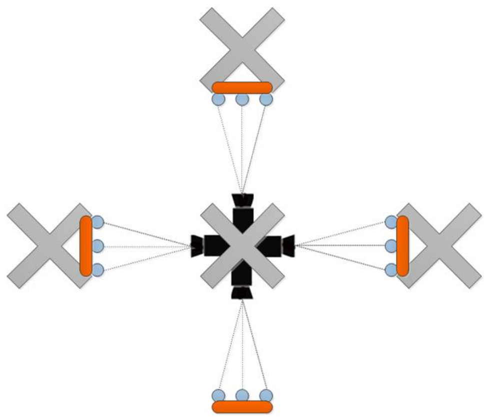

Figure 8: Network Topology of Swarm Cluster.

The algorithm scales to accommodate larger swarm formations by adding additional clusters, such as the one illustrated in Figure 9. A priority weighted algorithm will be used to resolve conflicts in the case of a follower receiving conflicting commands from multiple coordinators.

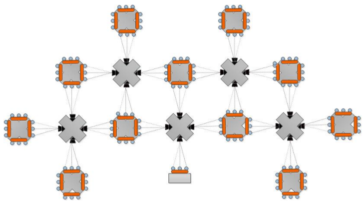

Figure 9: Network Topology of Multiple Clusters.

4.2 Routing Algorithm

The decision process performed by the coordinator in order to accurately send movement commands to all following quadrotors in the cluster is referred to as the Cluster Routing Algorithm (CRA).

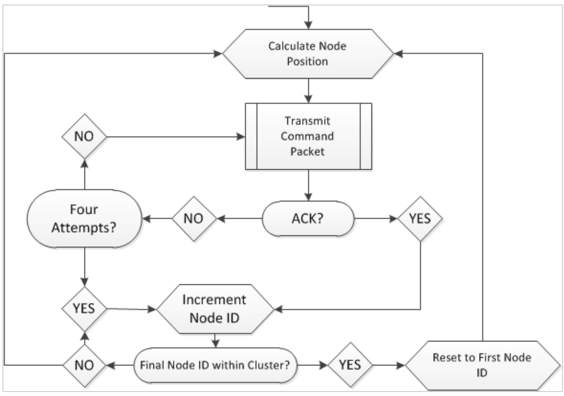

Figure 10: Cluster Routing Algorithm.

The purpose of the CRA is to issue commands to all followers within the cluster. The algorithm ensures that all commands are issued to the respective followers in a reliable manner, and that all followers receive equal amount of attention from their respective coordinator. The elements of the CRA, as depicted by Figure 10, are described in detail below.

Initialization. The coordinator assigns a node ID to the follower.

Calculate Follower Position. The position of follower of interest is calculated.

Transmit Command Node Packet. The movement commands are wirelessly transmitted to the appropriate follower in the form of a packet. The packet structure of the transmitted data is shown in Table 3.

Acknowledgment. The coordinator waits for a period of time for an acknowledgment from the respective follower to confirm the command was received. If the coordinator fails to receive an acknowledgment from the follower, it will retransmit the command packet. This process will continue for four times until which the coordinator will direct its attention to the next follower.

Increment Node ID. The coordinator increments the node ID so that it may focus on the next follower within the cluster.

4.3 Transmission Structure

The packet structure used in the transmission of data from the coordinator to followers as described in the routing algorithm section is shown in Table 3.

Table 3: Data frame structure of the transmitter.

Header	Node ID	Movement command	Error check

The data packet to be sent contains a header field, a unique node ID exclusive to each quadrotor, a movement command, and an error check is incorporated. An explanation of each of the Fields within the packet structure follows.

Header. Indicate the starting delimiter of the data packet.

Node ID. Address of the desired destination.

Movement command. Directs follower movement.

Error check. A checksum sequence is used for error detection within the packet.

5 AUTONOMOUS PROGRESS

There have been various small-scale tests performed with the control system, and information regarding the methodology of testing such a system has been gained. Our first step was to emulate the radio controller via a micro controller. Next, a suitable test environment and safe testing procedure was created for the quadrotor autonomous flight.

After securing the quadrotor to the test environment, the quadrotor was programmed to lift off autonomously. Instead of the quadrotor rising up in a strictly vertical motion, the quadrotor would fly in an angled direction depending on the state of the motors. After a short period of time, the quadrotor's flight control unit would stabilize and compensate for the motion of the quadrotor. Through this testing, it was validated that a larger testing environment will be needed for more advanced autonomous flight.

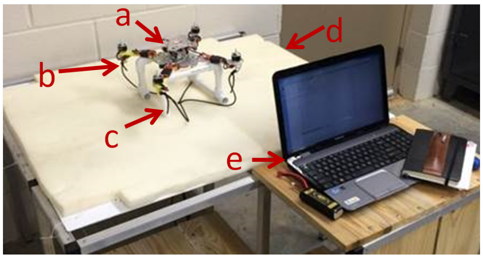

Figure 11: Basic autonomous test environment. a) Quadrotor. b) Platform to raise quadrotor. c) Tethers to each quadrotor arm d) Foam padding. e) Researcher workstation for programming. Note that tethers parachute cord which allows the researcher to work safely at the researcher workstation while quadrotor is testing

6 CONCLUSION

This paper presents the value of conducting research into autonomous quadrotor swarm formations. It also examines others' current research into quadrotor swarm formations and the drawbacks of decentralizing quadrotor control. The designs explained in this paper are towards autonomous quadrotor swarm control for uses that decentralized quadrotor systems are not optimal.

Our efforts have been placed into developing an autonomous control system integrated with an on-board vision system, explicating swarm formation algorithm, and determining the methods and precautions for safely testing quadrotor autonomous flight.

The limitations of our design are as follows: First, changes in quadrotor position from commands are small and safe. This results in a swarm that does not move agilely. Second, the vision system can determine it's distance to the beacon when the quadrotor is orthogonal to the coordinator, thus restricting formation options for the swarm.

7 FUTURE WORK

A larger and safer testing environment is necessary for further testing. The quadrotor test environment will be large enough for swarm formations and have foam padded floors and nylon fabric walls. Several cameras will facilitate accurate observation for testing and documentation.

Our team will implement full autonomous control by incrementing autonomous behavior. Our system will accommodate multiple quadrotors, and will have the capability of forming a network and will employ the vision system to establish and maintain swarm formations. In addition, the algorithm discussed will be implemented with a more powerful and practical vision system, eliminating the swarm's dependence on IR beacons.

8 ACKNOWLEDGMENTS

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